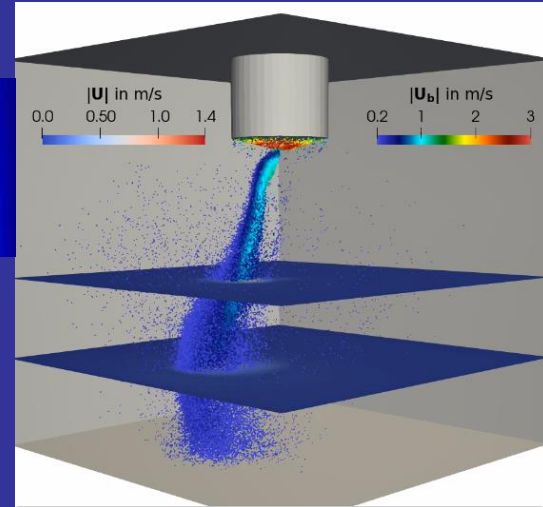
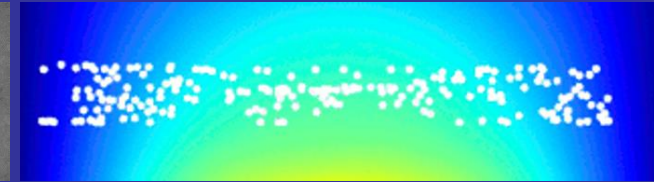
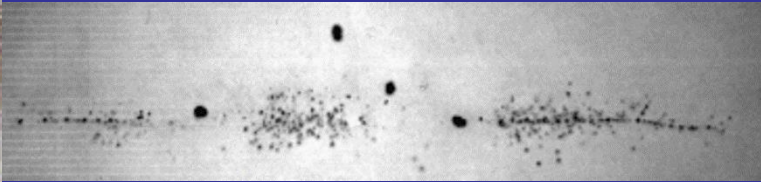


On modeling and simulation of acoustic cavitation



Robert Mettin¹, Christiane Lechner², Max Koch¹,
Sergey Lesnik³, Dwayne Stephens¹,
Atiyeh Aghelmaleki¹, Gunther Brenner³

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- 2) Institute of Fluid Mechancis and Heat Transfer, TU Wien
- 3) Institute of Applied Mechanics, Clausthal University of Technology

Content

VERY BRIEF REVIEW on ACOUSTIC CAVITATION:

- Acoustic cavitation and bubble structures
- Aspects for models and simulations

SOME EXAMPLES of SIMULATIONS:

- A single “jetting” bubble (“microscale”)
- Structure formation of a bubble group (“mesoscale”)
- Bubble and liquid motion at a sonotrode (“macroscale”)

CONCLUSION and OUTLOOK

Cavitation:

„The rupture of liquid under tensile stress
and the accompanying phenomena“

- appearance of bubbles (nucleation)
- bubble dynamics (oscillation, translation, splitting, merging, sound emission, ...)
- collapse effects (shock waves, erosion, chemistry, luminescence, ...)
- collective effects (structure formation, sound propagation, ...)

Cavitation:

„The rupture of liquid under tensile stress
and the accompanying phenomena“

Historically first and technically very important:
HYDRODYNAMIC cavitation: tensile stress in **flows**



Ship propeller tip cavitation

Higuchi, Rogers, and Arndt (1986)

Cavitation:

„The rupture of liquid under tensile stress
and the accompanying phenomena“

Main topic now:

ACOUSTIC cavitation: tensile stress by **intense acoustic fields**

acoustic **shock wave** induced nucleation

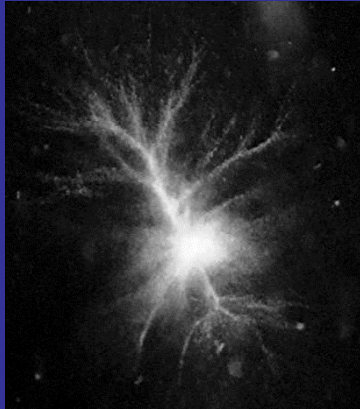


exposure 10 ns, interframe time 500 ns

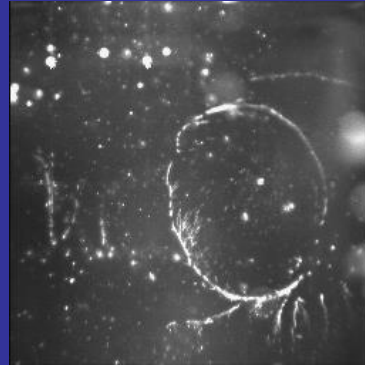
Sankin, Mettin, Geisler, Teslenko, Lauterborn, DAGA 2001

Acoustic cavitation structures in **continuous waves** ($\sim 20 \dots 100$ kHz)

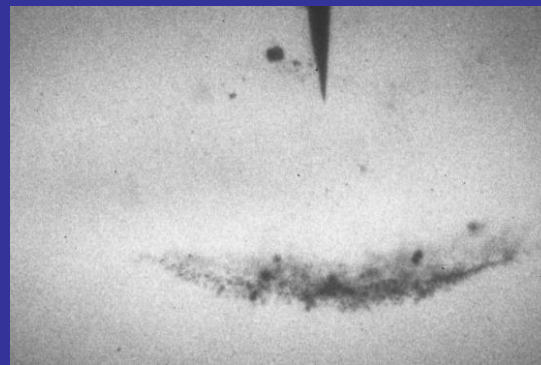
“Zoo”, depending on sound field, liquid, geometry etc.



filament



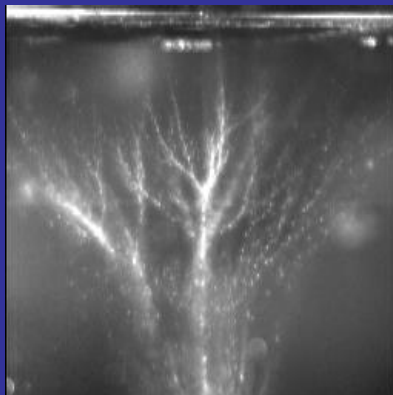
bow/ring



double layer



sonotrode cloud



conical structure



flare structure

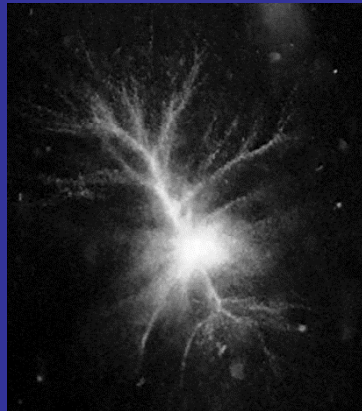


smoker

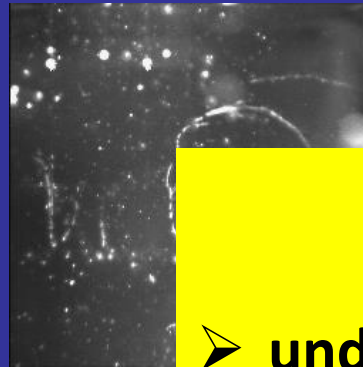
and others...

Acoustic cavitation structures in **continuous waves** ($\sim 20 \dots 100$ kHz)

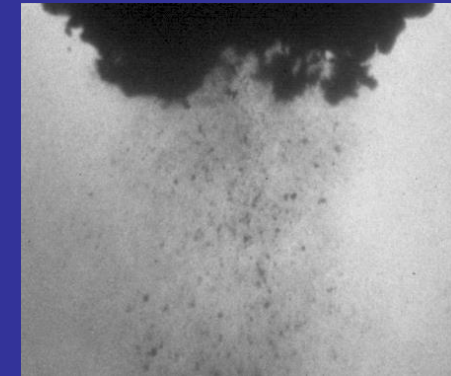
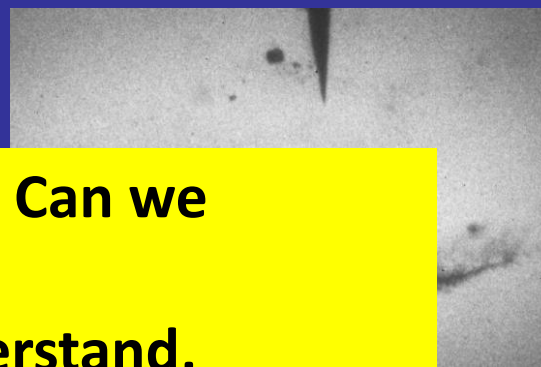
“Zoo”, depending on sound field, liquid, geometry etc.



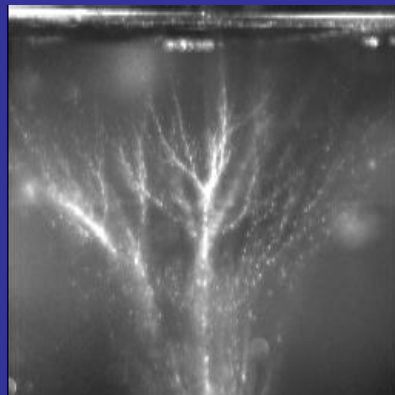
filament



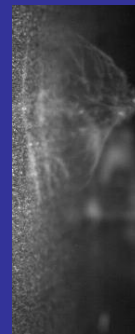
bow/



sonotrode cloud



conical structure



Can we

- **understand,**
- **model and simulate**
- **predict**
- **optimize and design**

**acoustic cavitation
structures
???**



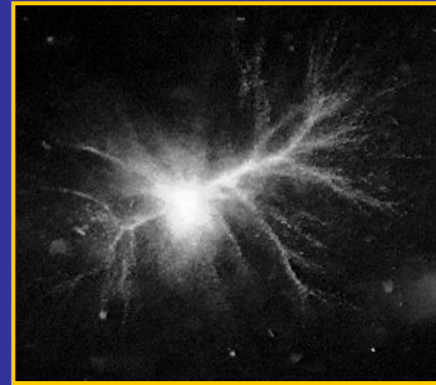
smoker

and others...

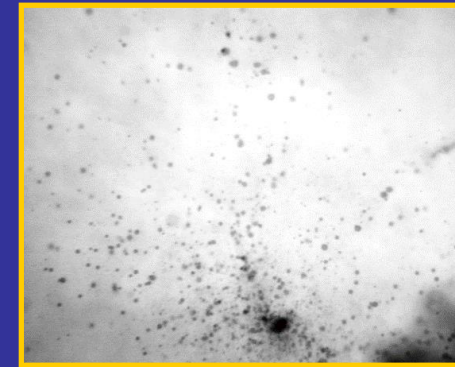
Acoustic cavitation is a **multiscale** phenomenon



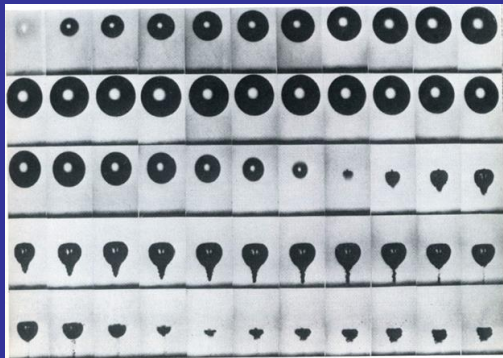
Cleaning bath ($\approx \text{dm} \dots \text{m}$)
Degassing ($\approx \text{min}$)
Erosion ($\approx \text{s}$)



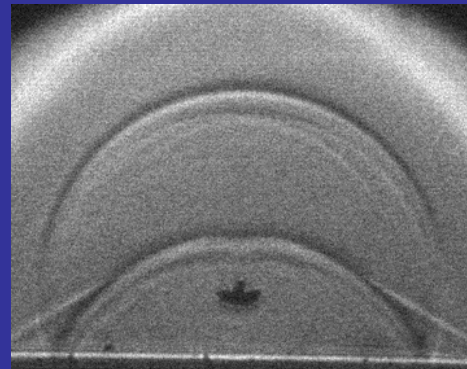
Bubble structures ($\approx \text{cm}$)
Structure formation ($\approx \text{s}$)
Sloshing ($\approx \text{s}$)



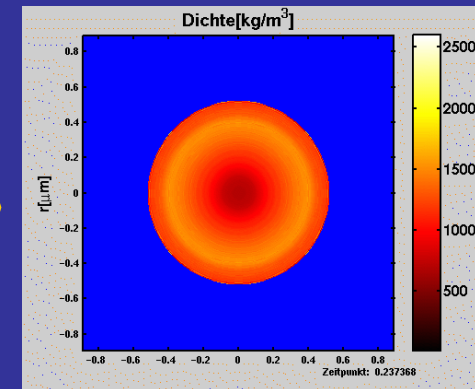
Bubble clusters, streamers ($\approx \text{mm}$)
Inter-collision times ($\approx \text{ms}$)



Bubble sizes ($\approx 1 \dots 100 \mu\text{m}$)
Bubble oscillations ($\approx 1 \dots 100 \mu\text{s}$)



Bubble collapse, jet ($\approx \mu\text{m}$)
Compression times ($\approx \mu\text{s}$)



Hot spot, shock waves ($< \mu\text{m}$)
Chemistry, luminescence ($\approx \mu\text{s} \dots < \text{ns}$)

Acoustic cavitation is a “multiphysics” phenomenon

Transducer → multiphase medium, complex impedance loads

Sound Wave → propagation in multiphase (bubbly) medium

Nucleation → nuclei distribution, activation thresholds, diffusion

Bubble oscillations → nonlinear, coupled
viscous + thermal + radiation damping, shock waves
evaporation/condensation, chemistry, luminescence

Bubble motion → variety of forces: primary Bjerknes (pressure gradient)
added mass, drag, buoyancy
lift, Basset, ...

Bubble interaction → secondary Bjerknes, collision/splitting

Liquid motion → turbulence

Boundary conditions → geometry, objects (…and more → further things)

Acoustic cavitation is a “multiphysics” phenomenon

Transducer → multiphase medium, complex impedance loads

Sound Wave → propagation in multiphase (bubbly) medium

Nucleation →

Bubble

An “all-comprising” model is not (yet) possible

→ Restriction to some aspects

Bubble

**→ Identify most relevant (or tractable :-)
phenomena**

shock waves
luminescence

velocity gradient)
acoustic

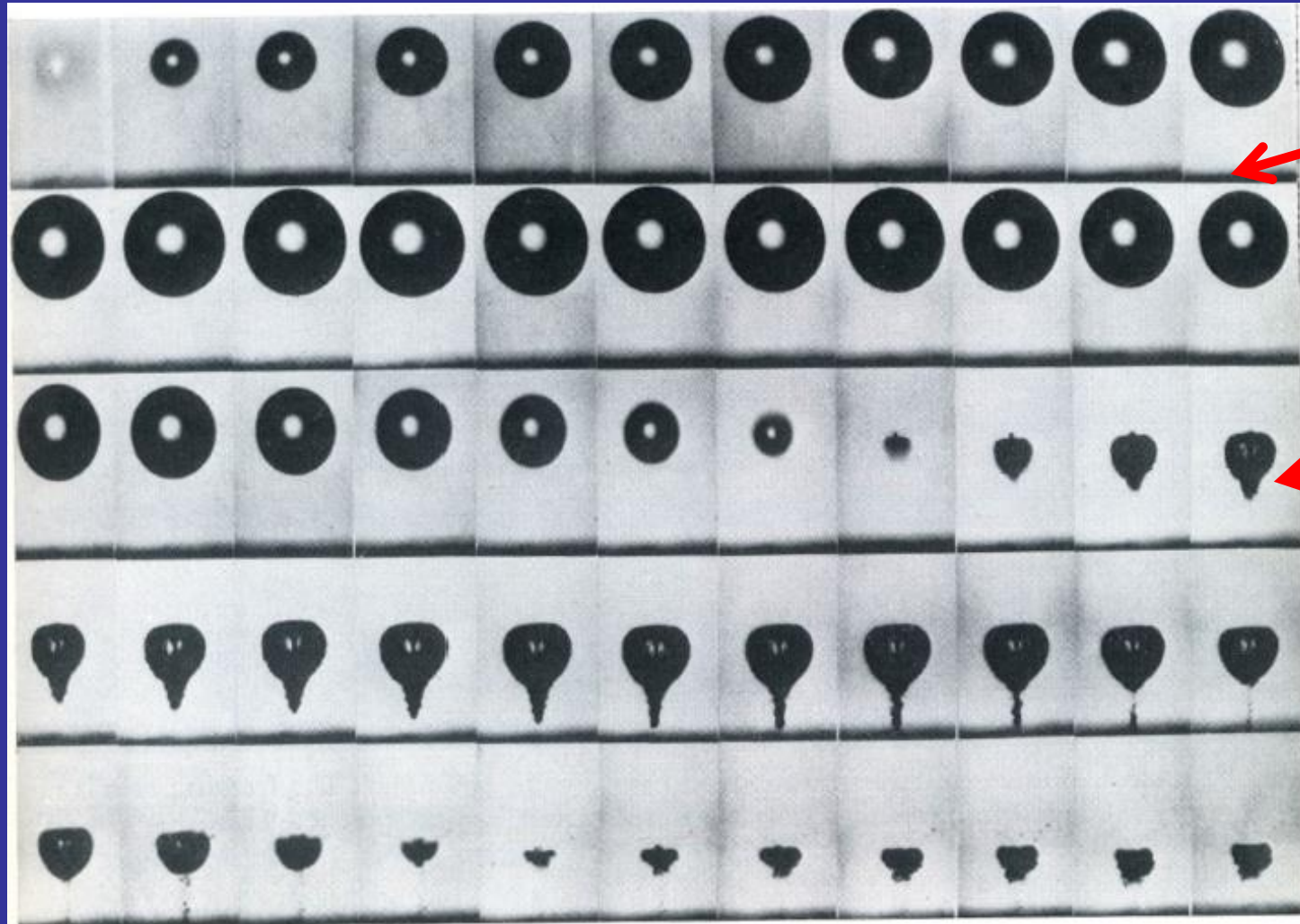
Bubble interaction → secondary Bjerknes, collision/splitting

Liquid motion → turbulence

Boundary conditions → geometry, objects

(...and more → further things)

Collapse of a single bubble



solid
boundary

„jetting“

Lauterborn & Bolle (1975)
experimental „proof of jet“

Jetting due to gravity

Max Koch, 2024



DΦI

Max Koch

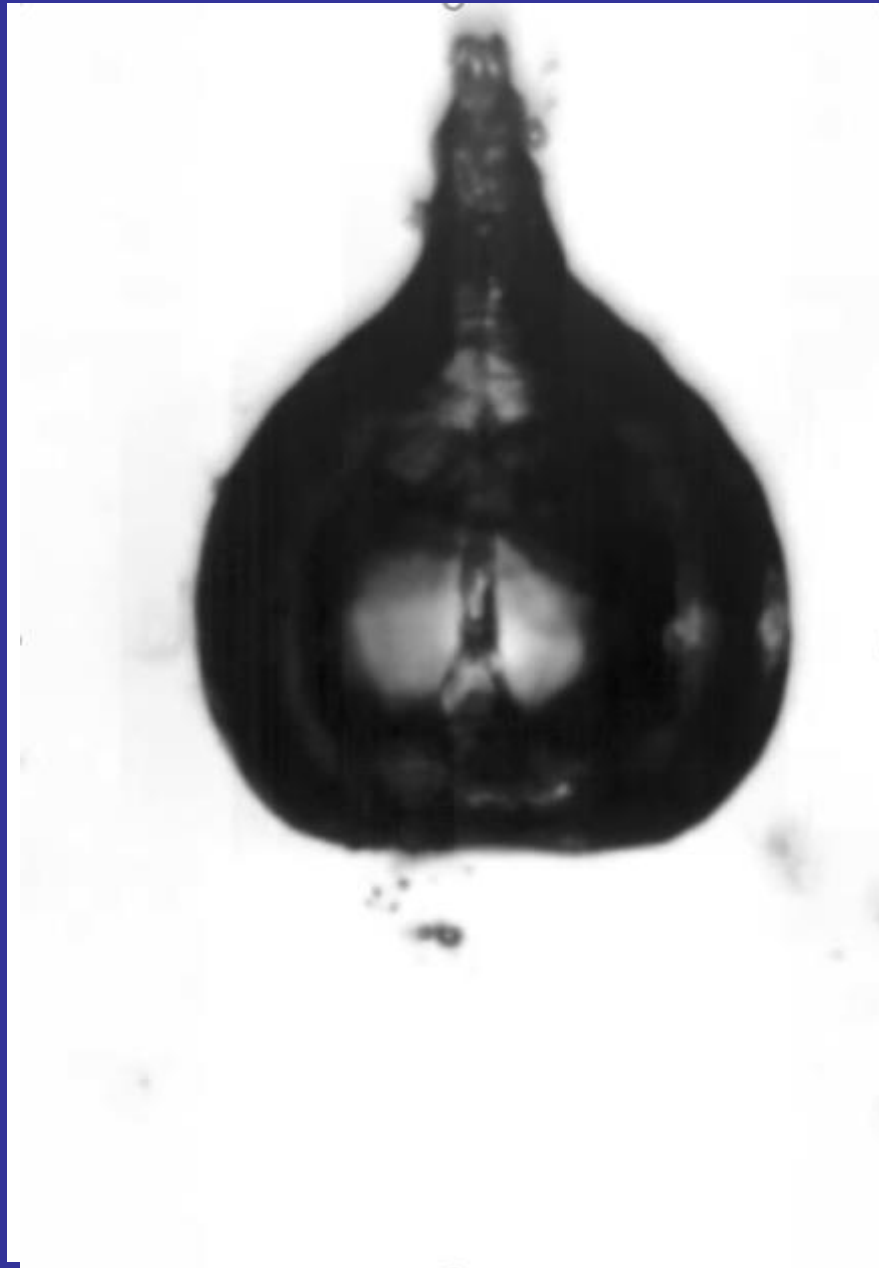
Jetting due to gravity

Max Koch, 2024

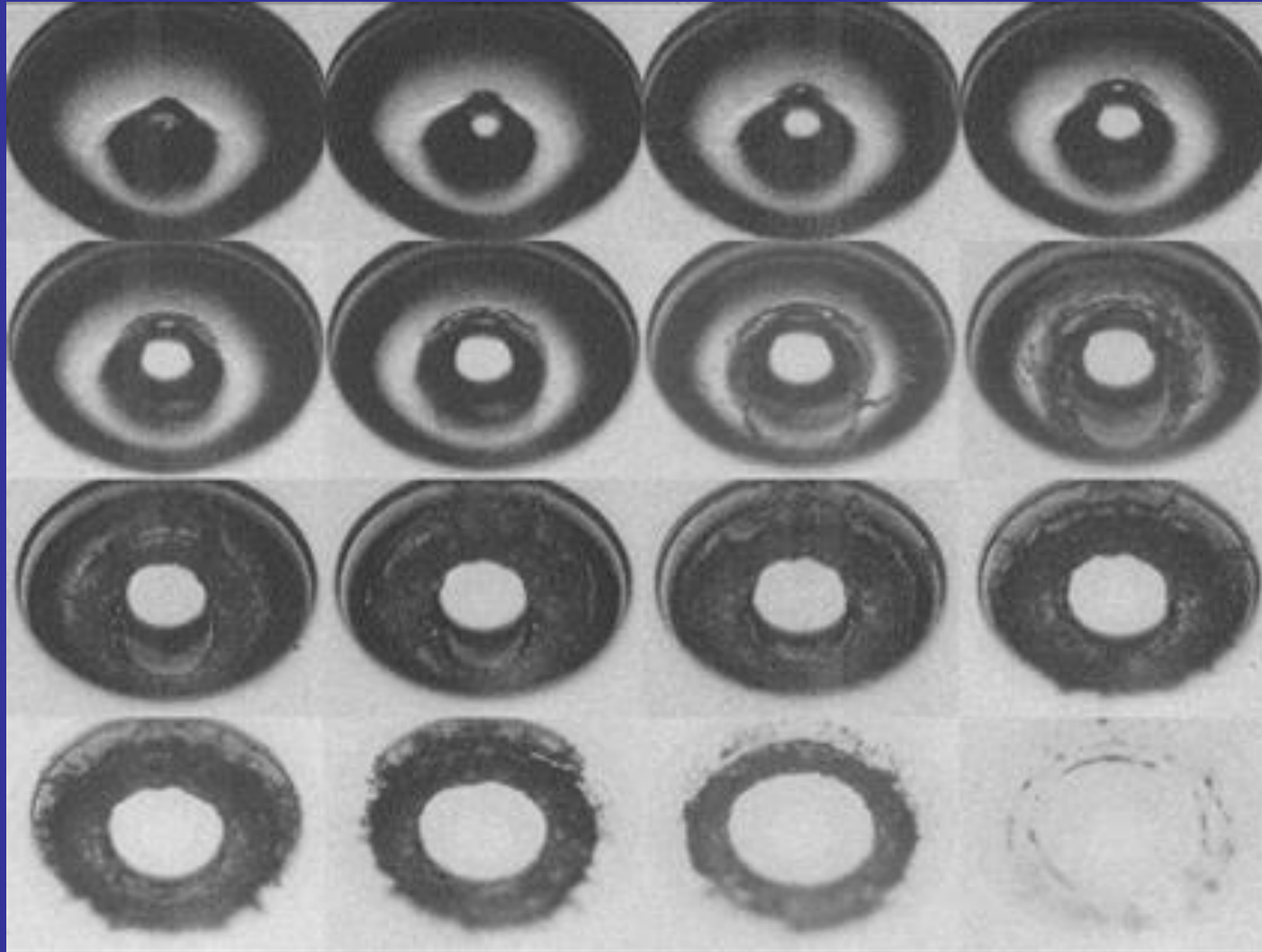


Jetting due to gravity

Max Koch, 2024



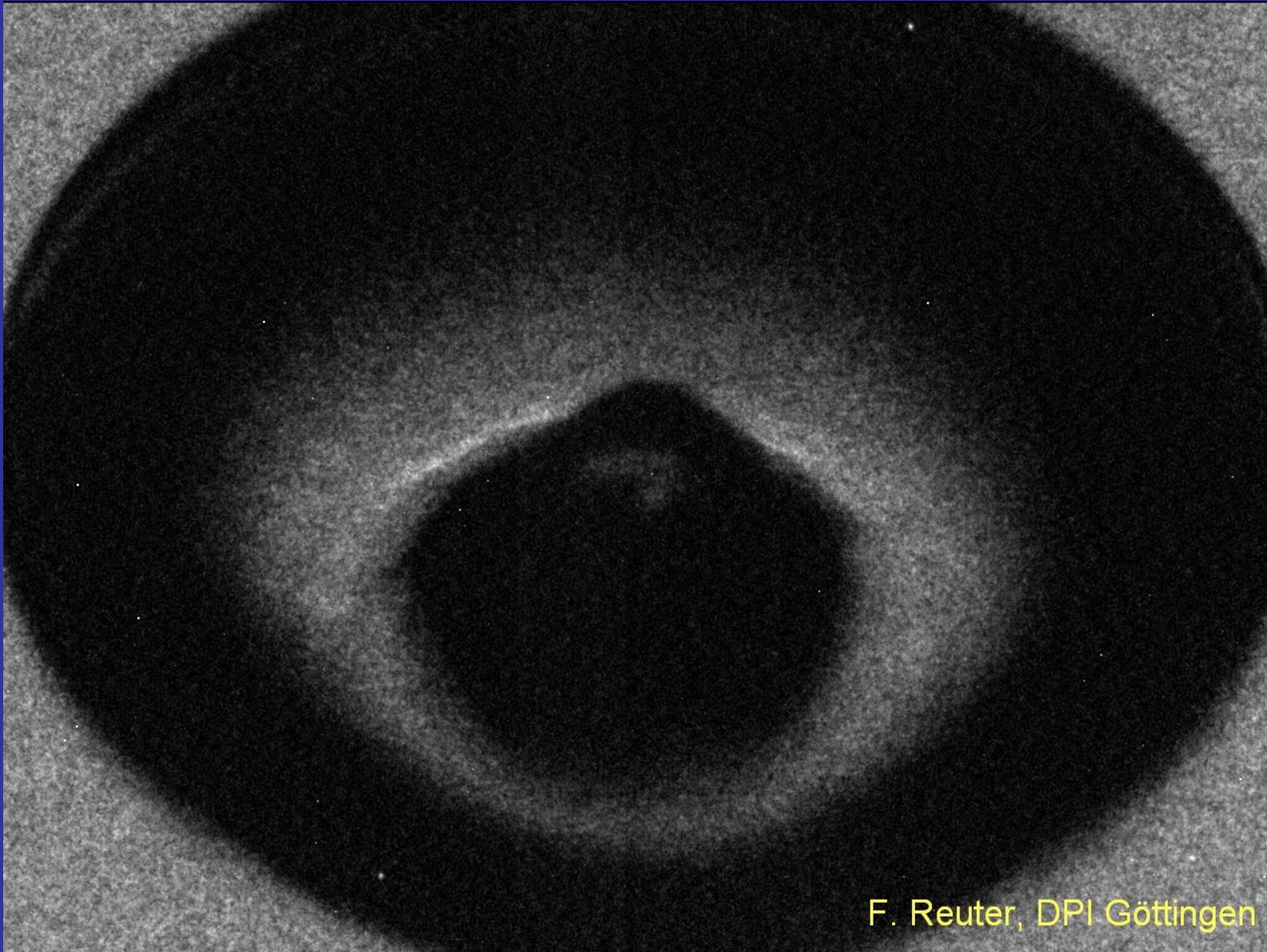
Jetting at the solid surface – oblique view through glass plate



exposure 10 ns, interframe time 800 ns, width 1 mm

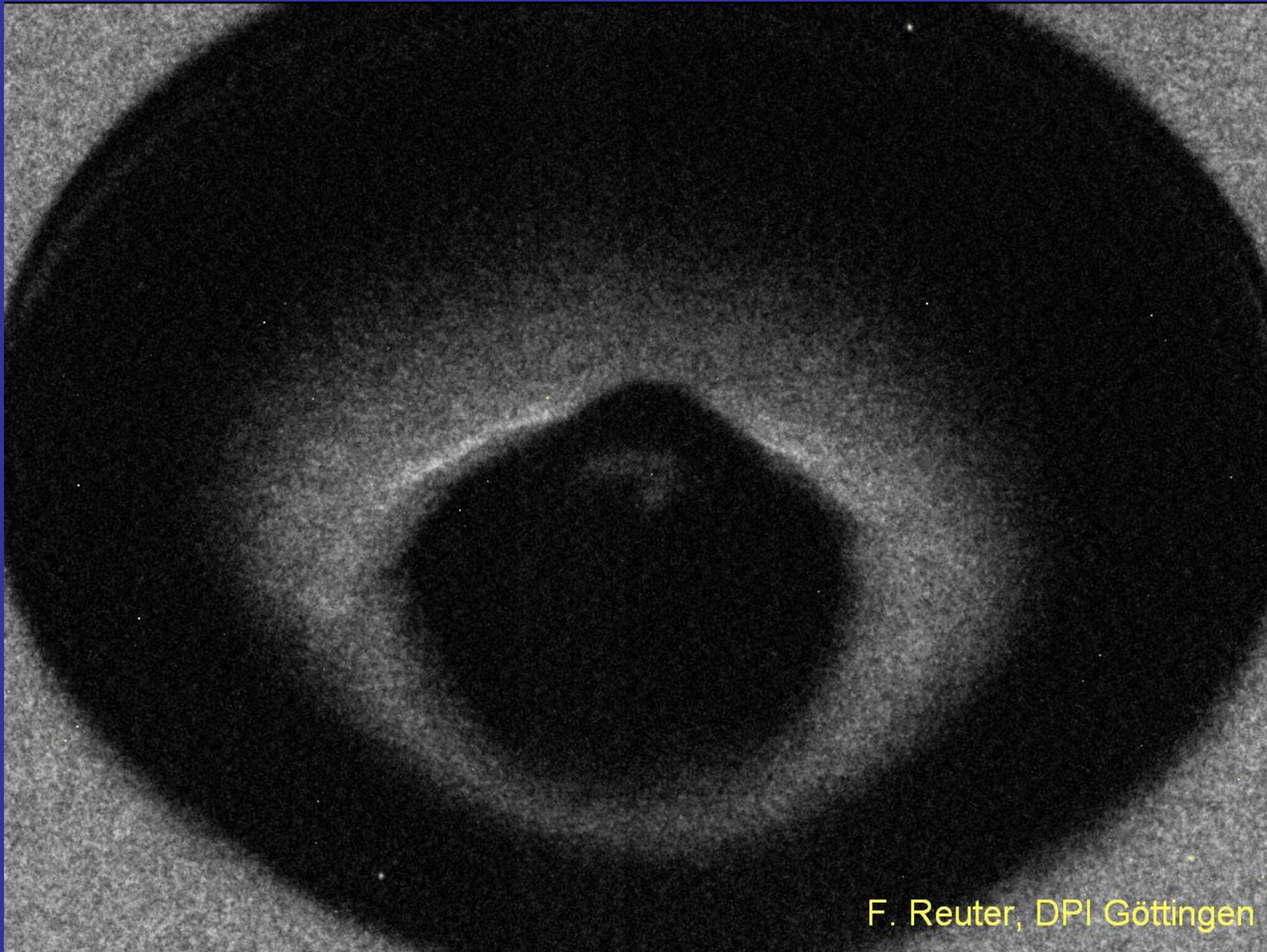
F. Reuter & R. Mettin, *Ultrason. Sonochem.* 29 (2016)

Jetting at the solid surface



F. Reuter, DPI Göttingen

Jetting at the solid surface



F. Reuter, DPI Göttingen

Bubble model and numerical implementation

Volume of fluid method, volume fraction $\alpha_l \in [0, 1]$

Navier-Stokes equations, equations for variables α_l, \mathbf{U}, p

$$\begin{aligned}\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{U}) &= 0, \\ \frac{\partial(\rho \mathbf{U})}{\partial t} + \nabla \cdot (\rho \mathbf{U} \otimes \mathbf{U}) &= -\nabla p + \nabla \cdot \mathbb{T} + \mathbf{f}_\sigma \\ \frac{\partial(\alpha_l \rho_l)}{\partial t} + \nabla \cdot (\alpha_l \rho_l \mathbf{U}) &= 0,\end{aligned}$$

density $\rho = \alpha_l \rho_l + (1 - \alpha_l) \rho_g$, \mathbf{f}_σ surface tension term

$\rho_l(p), \rho_g(p)$ from EoS \rightarrow liquid: Tait equation $(p + B_T) \rho_l^{-n_T} = \text{const}$

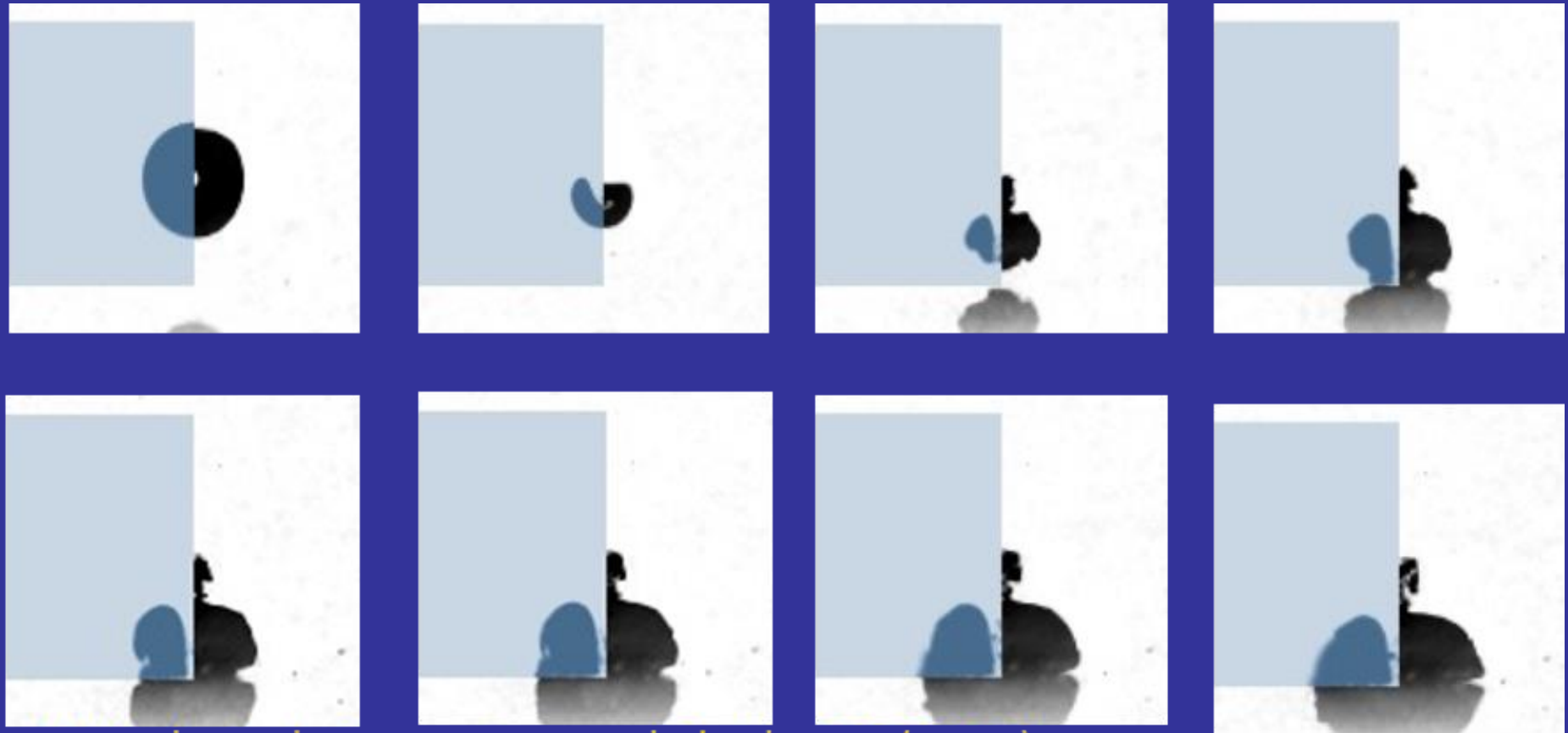
\rightarrow gas: ideal gas, adiabatic $p \rho_g^{-\gamma_g} = \text{const}$

\mathbb{T} viscous stress tensor, Newtonian fluid

implementation in OpenFOAM (FVM), Koch et al. (2016) *Comput. Fluids* 126 71

Jetting at the solid surface

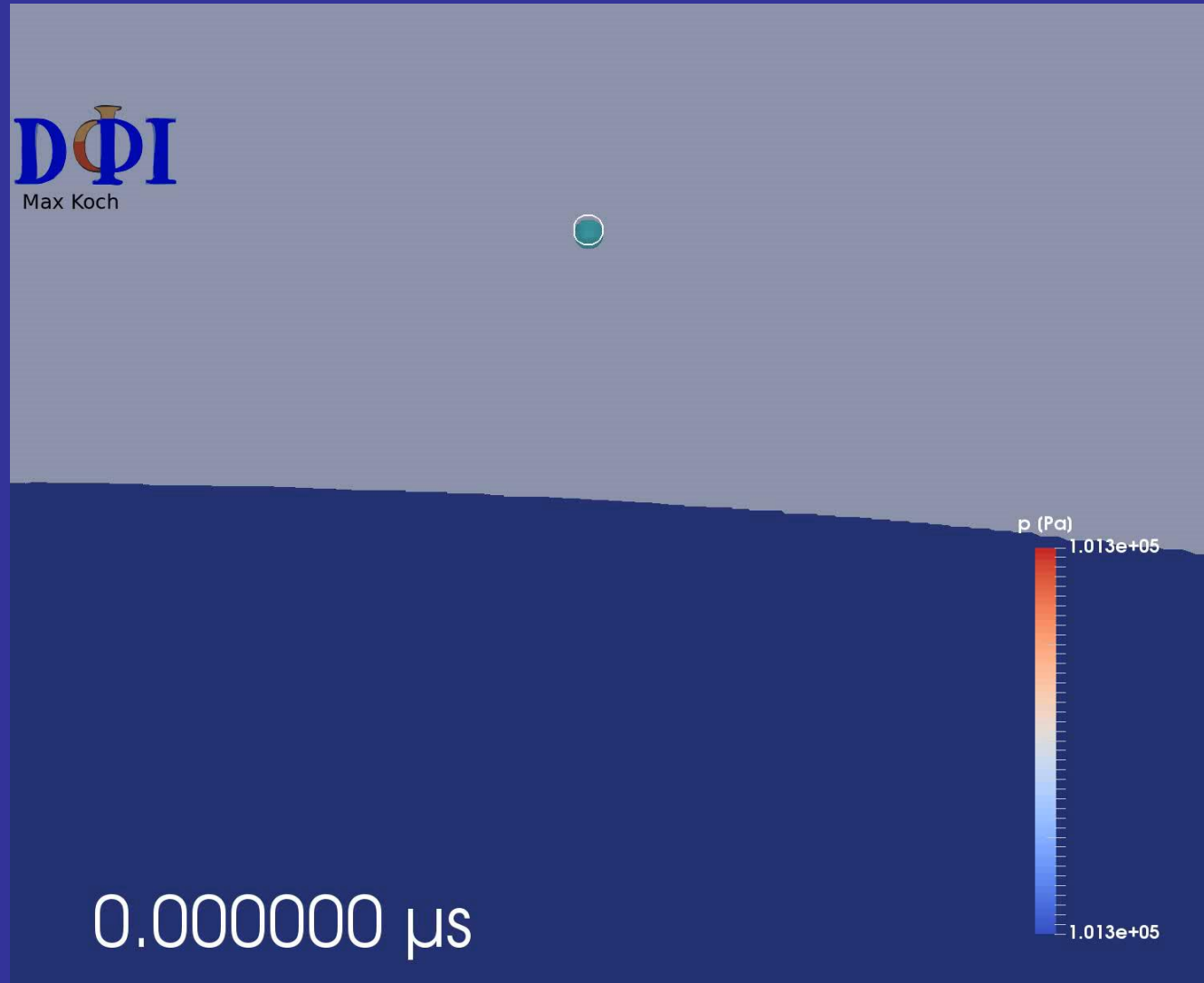
experiment
and
calculation
(VoF)



M. Koch et al., Computers and Fluids 126 (2016)

Jetting at the solid surface

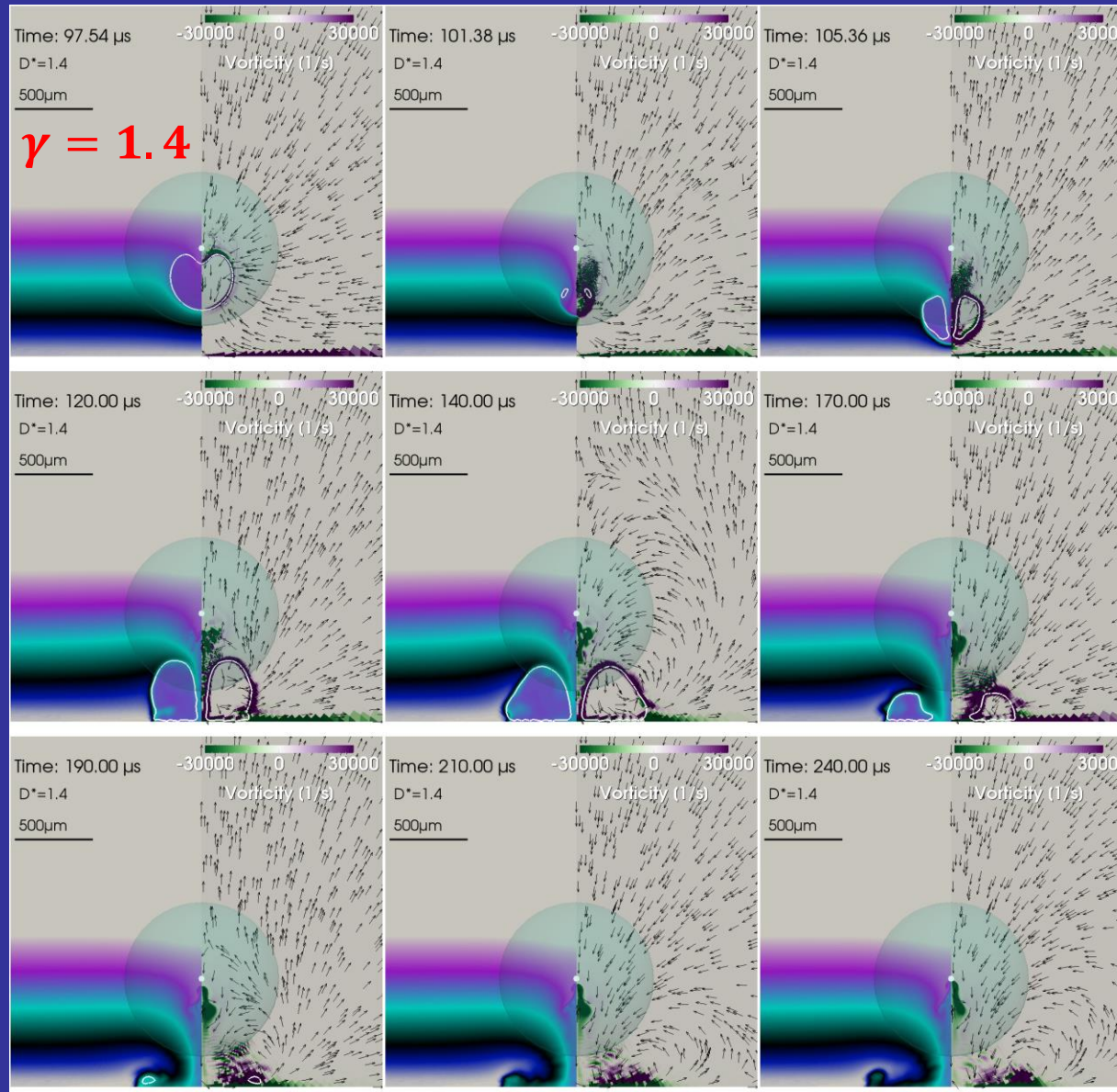
Oblique jet
near an
edge



Rosselló, Koch et al., 2024

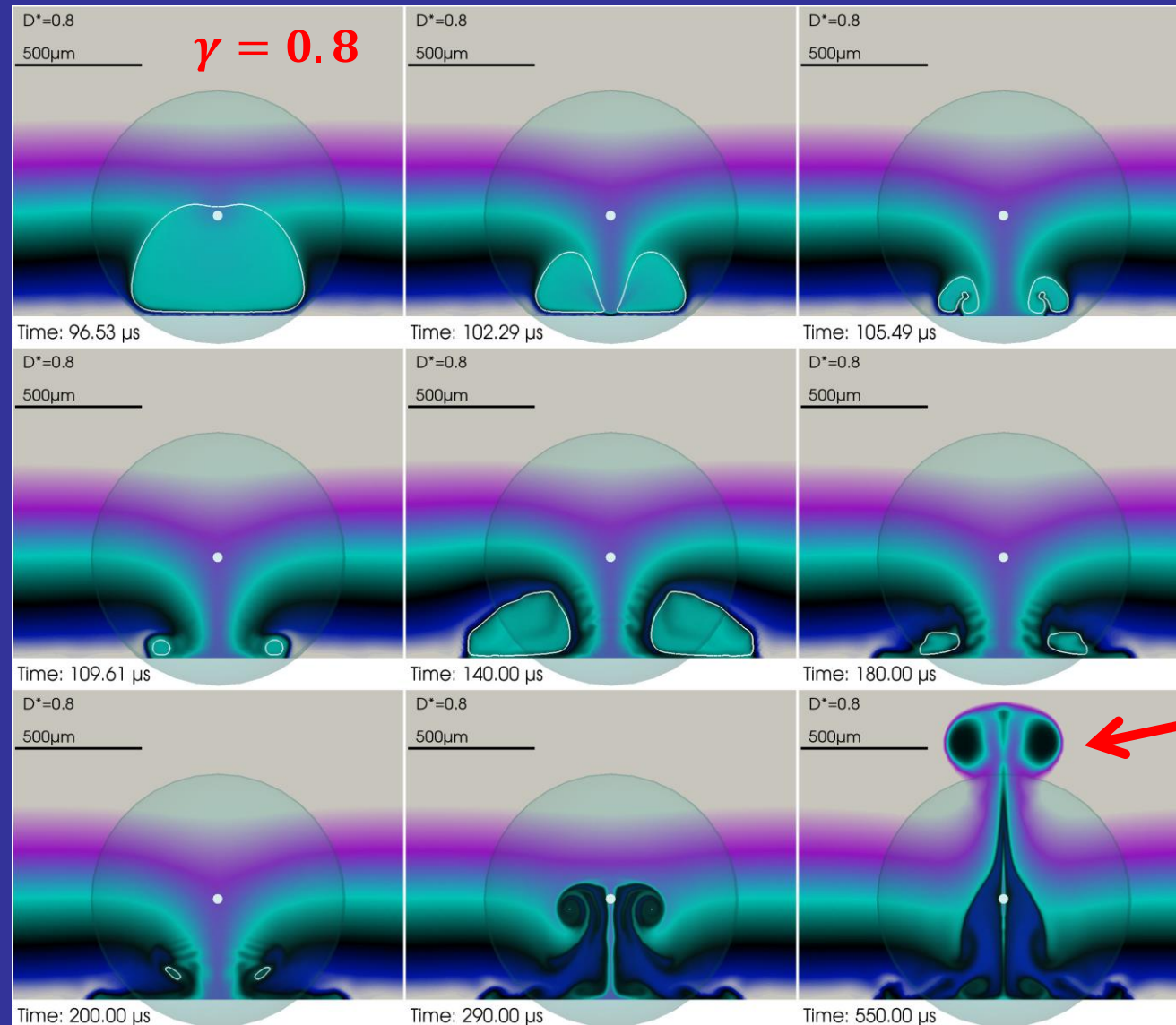
Vortex flows

Simulations with
FVM/VoF



Vortex flows

Simulations with
FVM/VoF

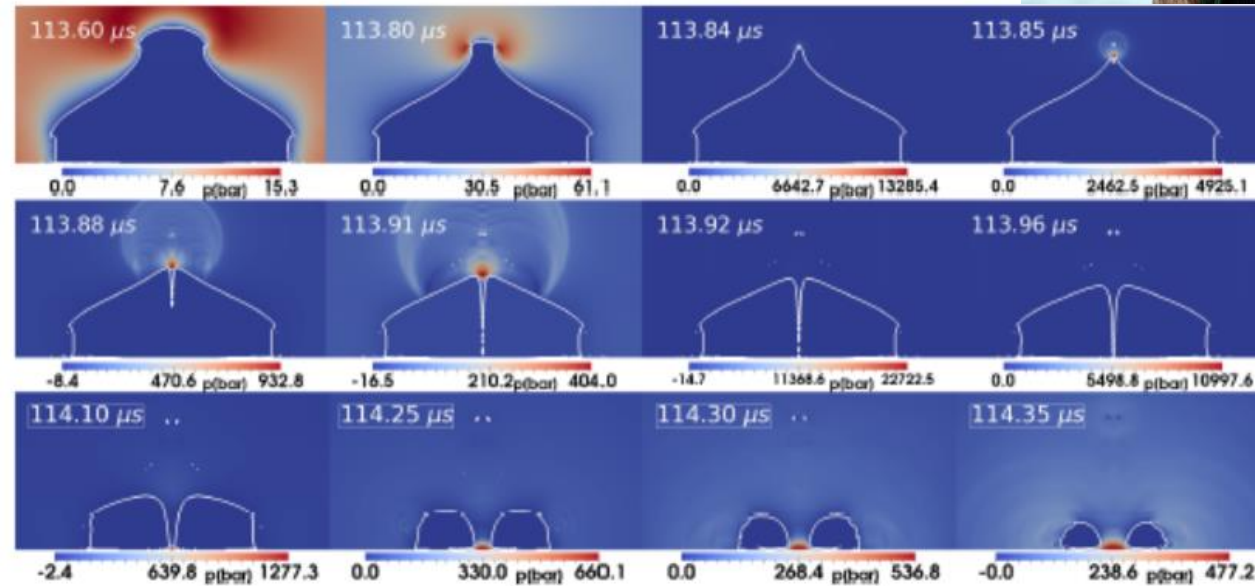


liquid
transport

Extremely fast jets: numerical prediction

Expansion and collapse of a bubble with $D^* = 0.048$

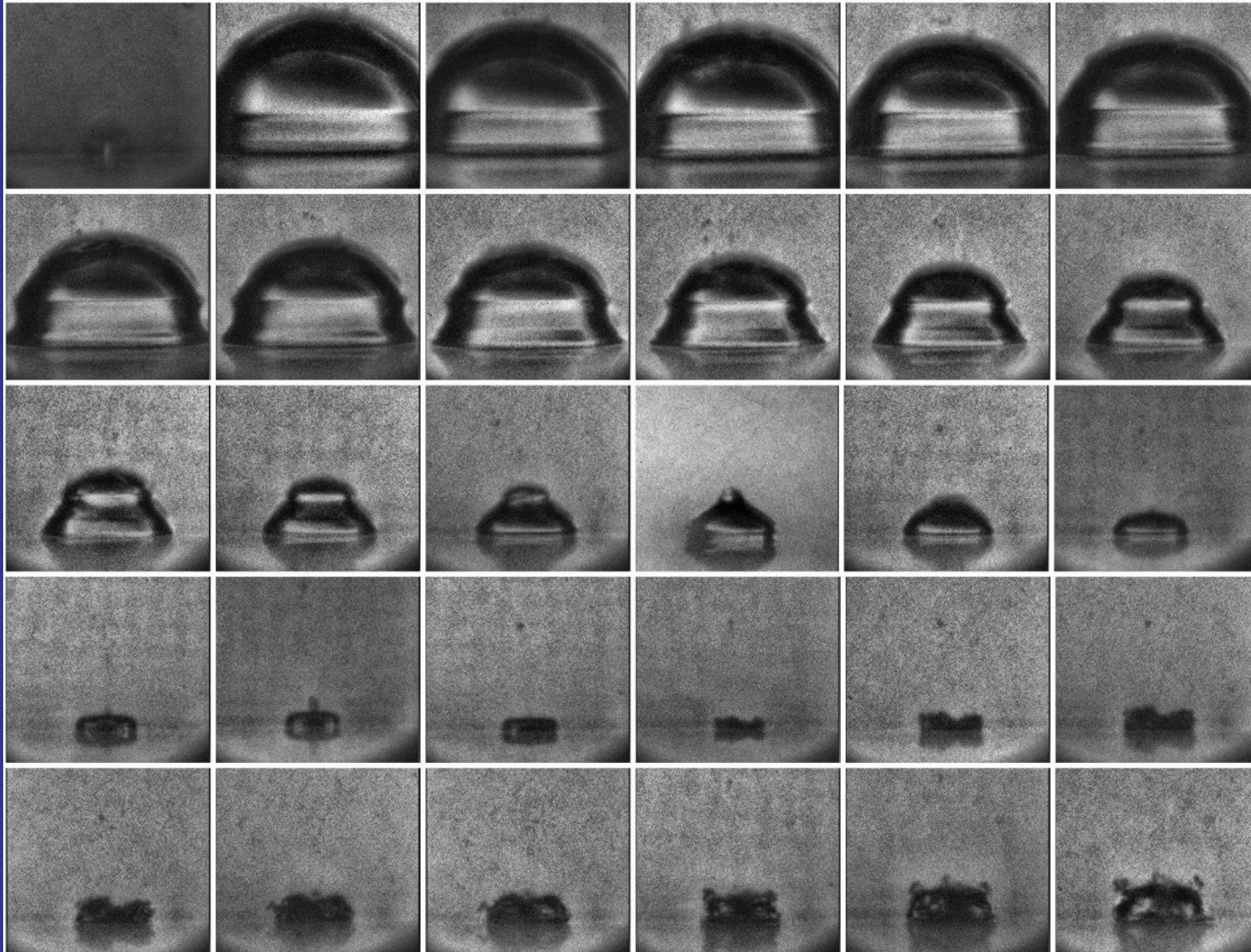
pressure in bar



Christiane
Lechner
(now TU Vienna)

jet speed is of the order of 1000 m/s

Extremely fast jets: experimental proof



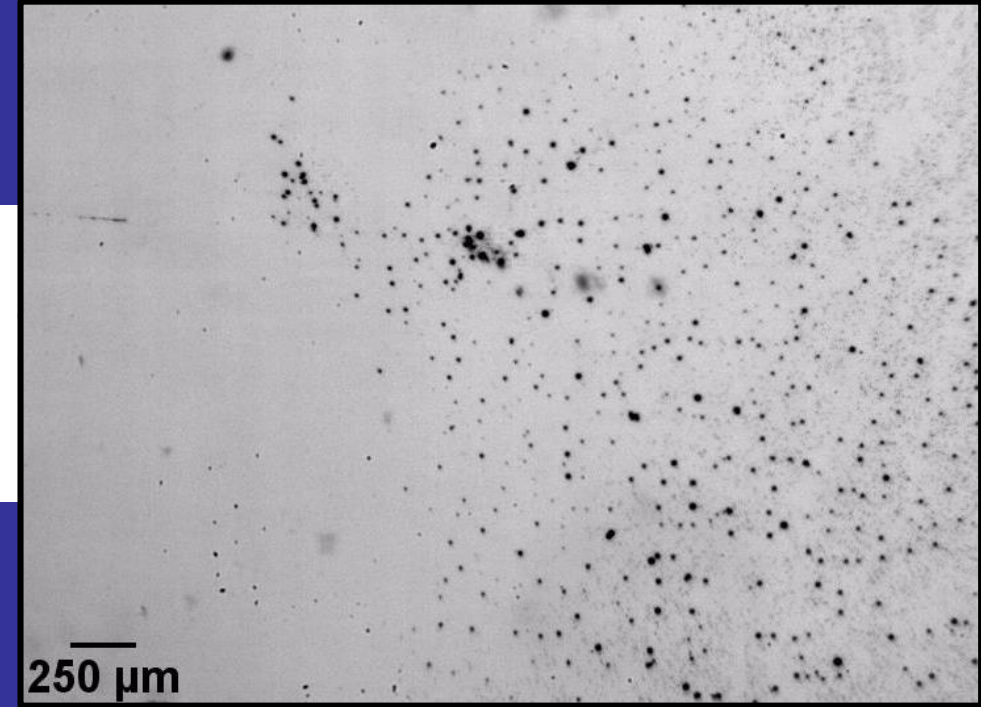
Max Koch

Bubble interaction in multibubble fields

Force balance **averaged over one acoustic cycle** :

$$\mathbf{F}_M^i + \mathbf{F}_D^i + \mathbf{F}_{B1}^i + \sum_{j \neq i} \mathbf{F}_{B2}^{j,i} = \mathbf{0} \quad ,$$

One can solve (coupled) equations of motion of individual bubbles ("particles") for a given pressure distribution:



Water + NaCl + Ar @ 80 kHz

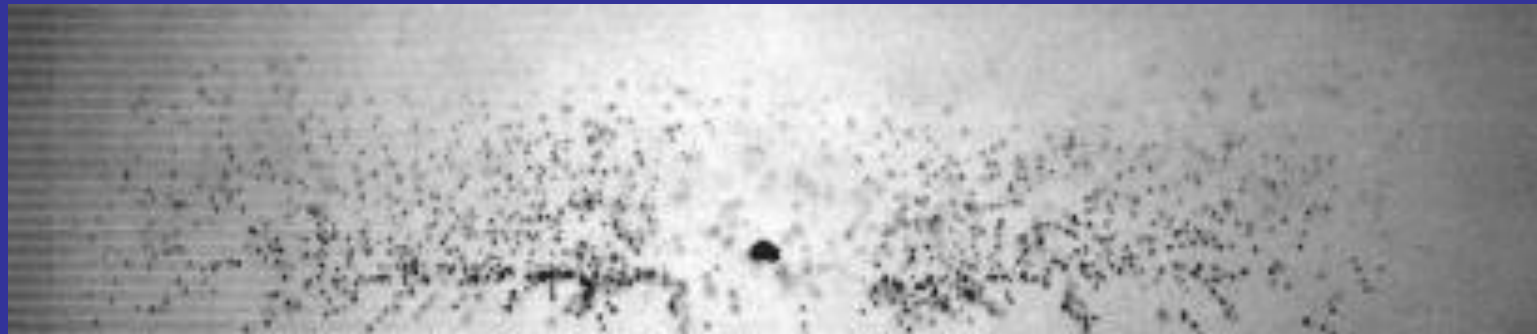
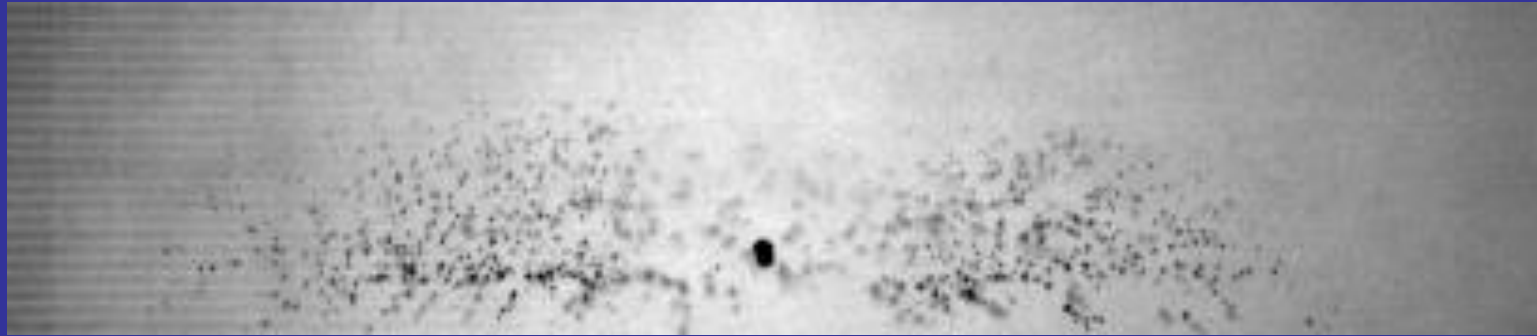
→ **Simulations of cavitation structure formation by particle models**

Example: Stephens, Rosselló, Mettin 2021

Bubbles seeded within an **elongated cylindrical region**

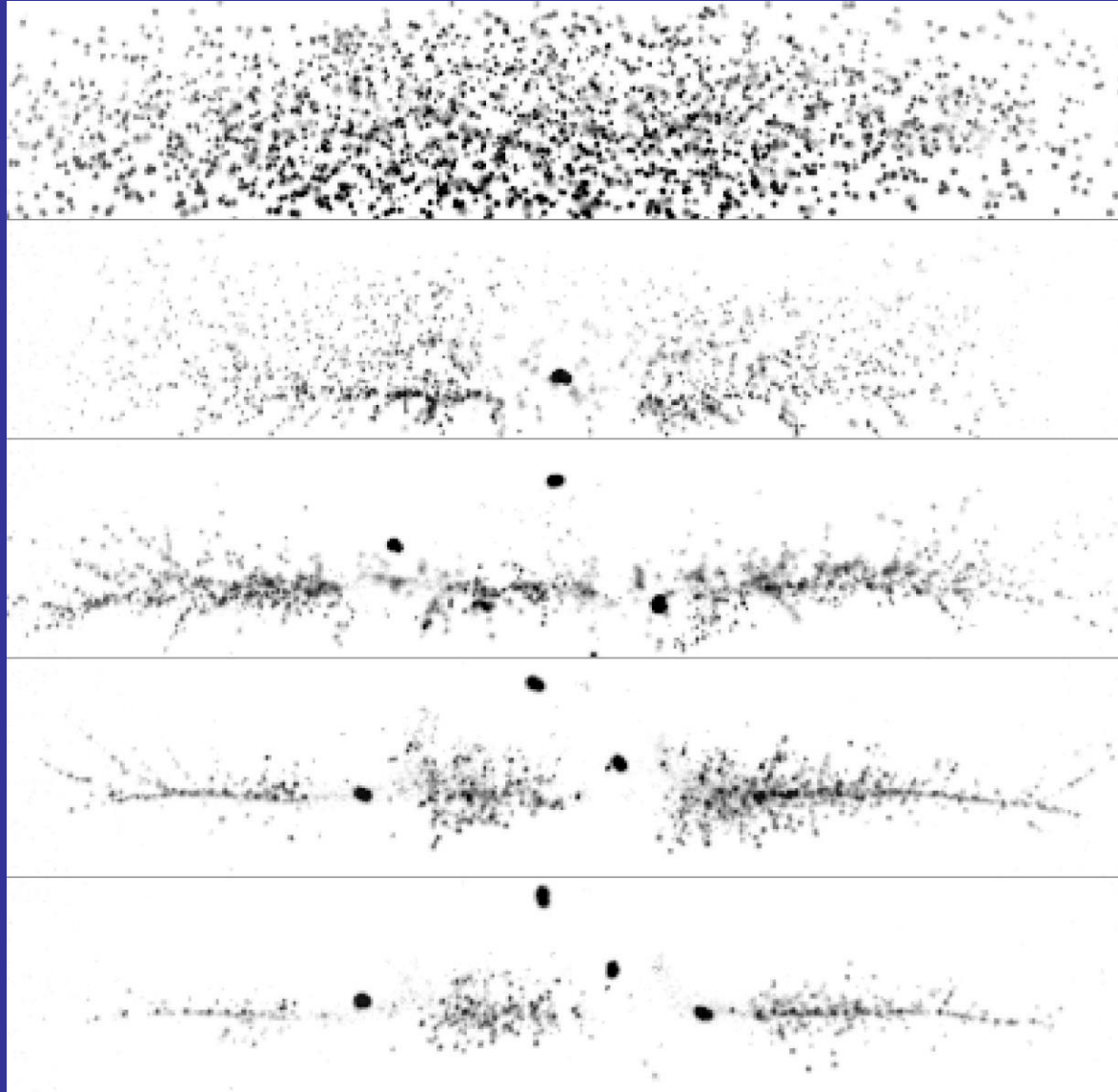


while the bubble population is uniform, oscillations follow P_{AC}



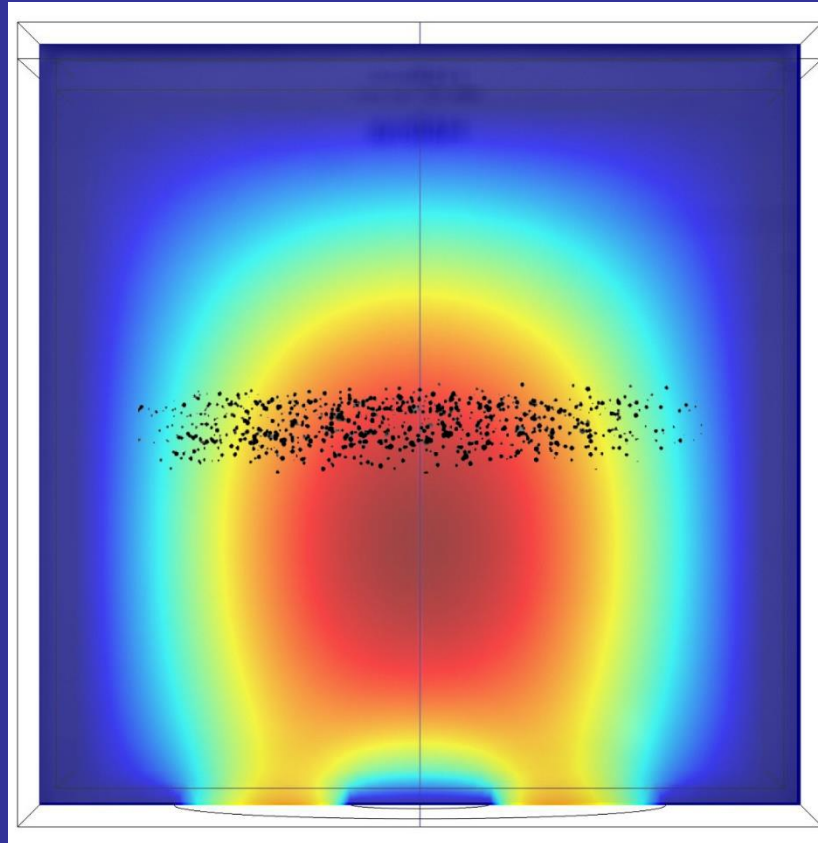
later, the bigger bubbles significantly distort the acoustic field

Example: Stephens, Rosselló, Mettin 2021

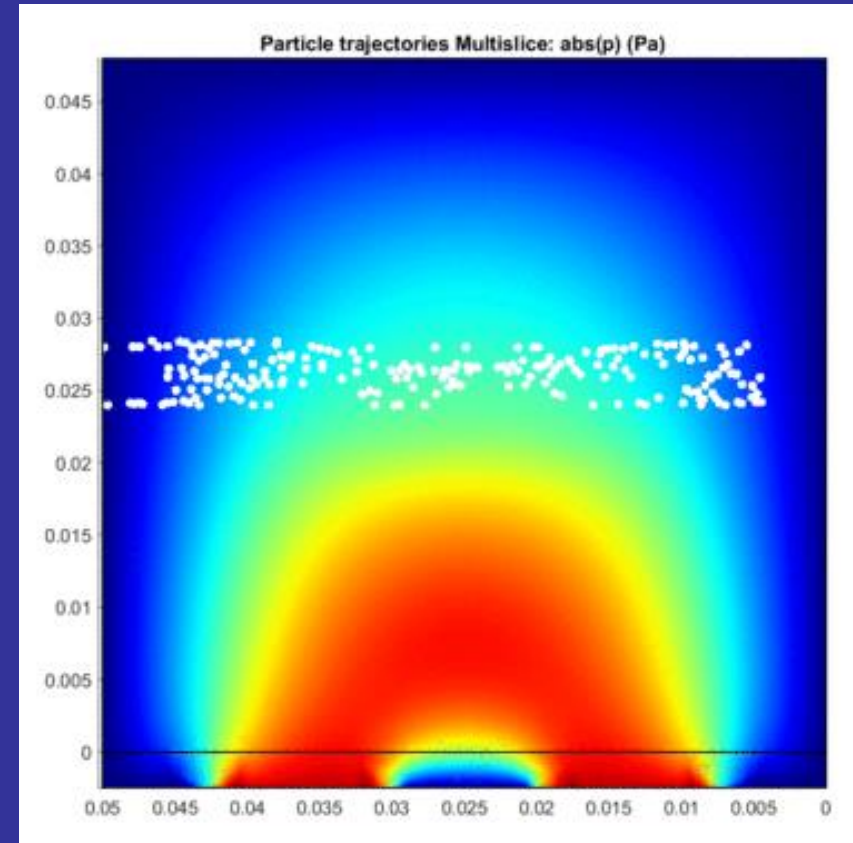


Pressure field

Calculated pressure field indeed „flattened“ by presence of bubbles



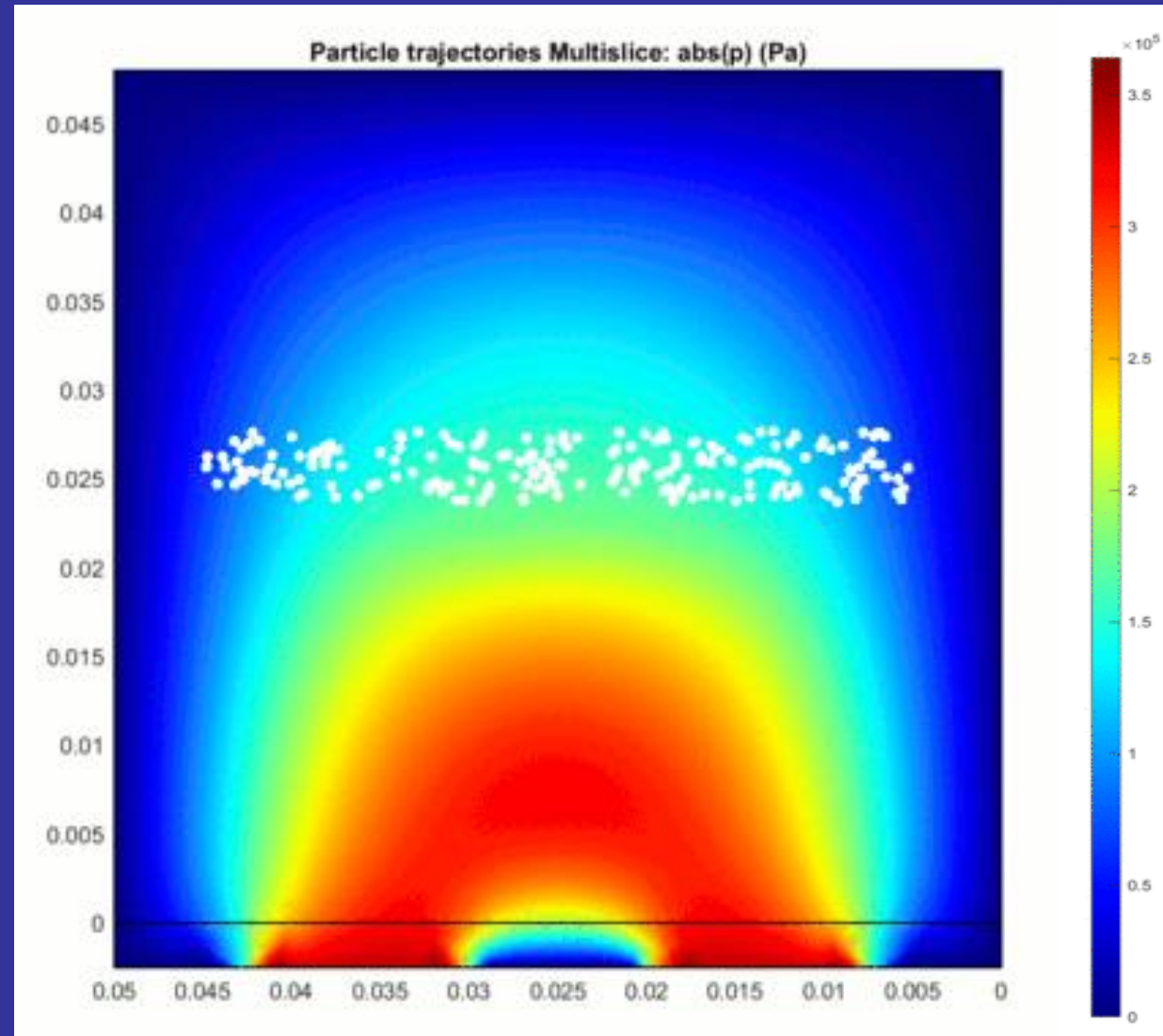
No bubbles for field calculation +
experimental bubble positions



Simulated bubble positions +
resulting pressure field

Bubble merging

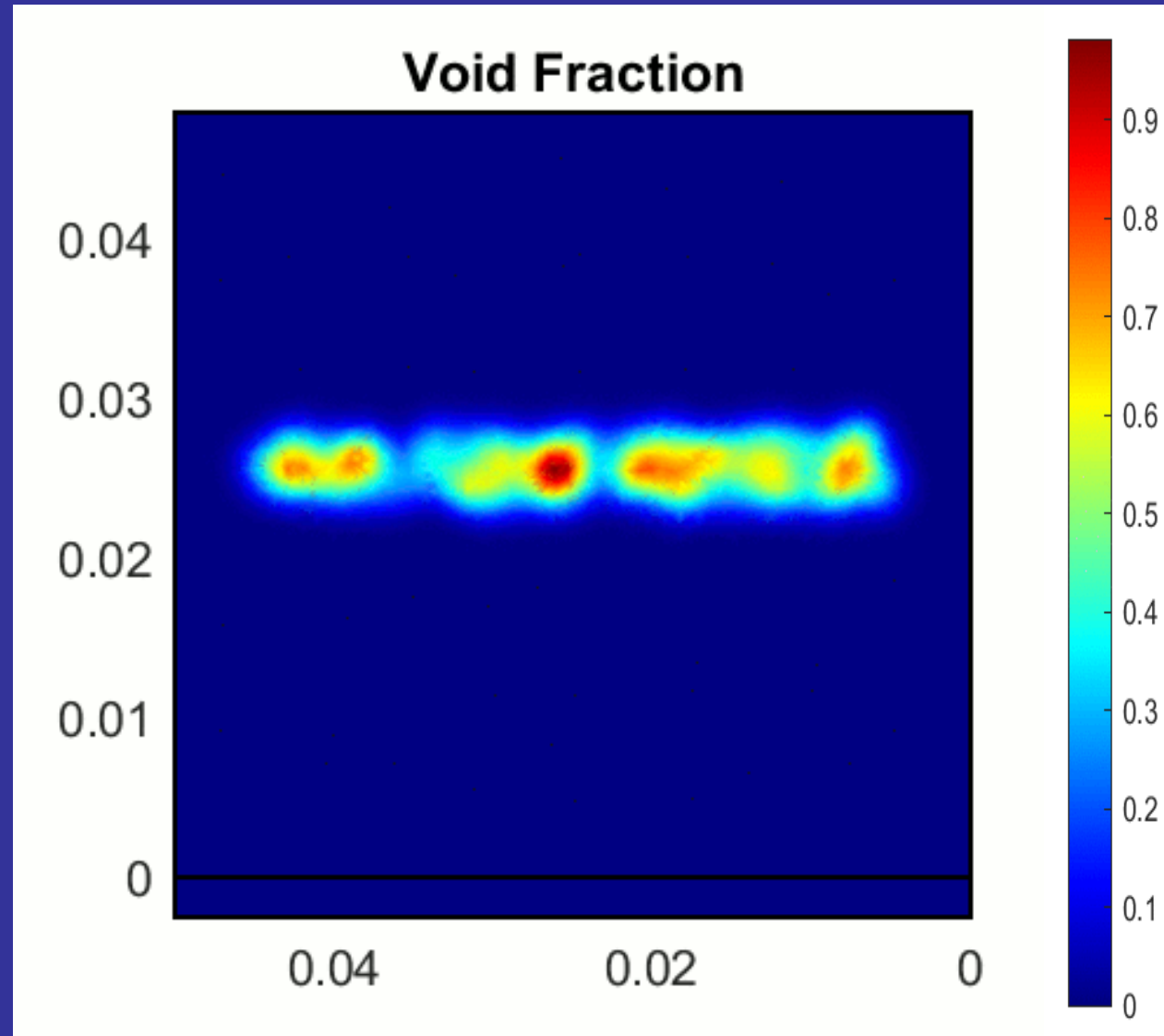
Bubble attraction and motion to the center



Simulation with
COMSOL / Matlab

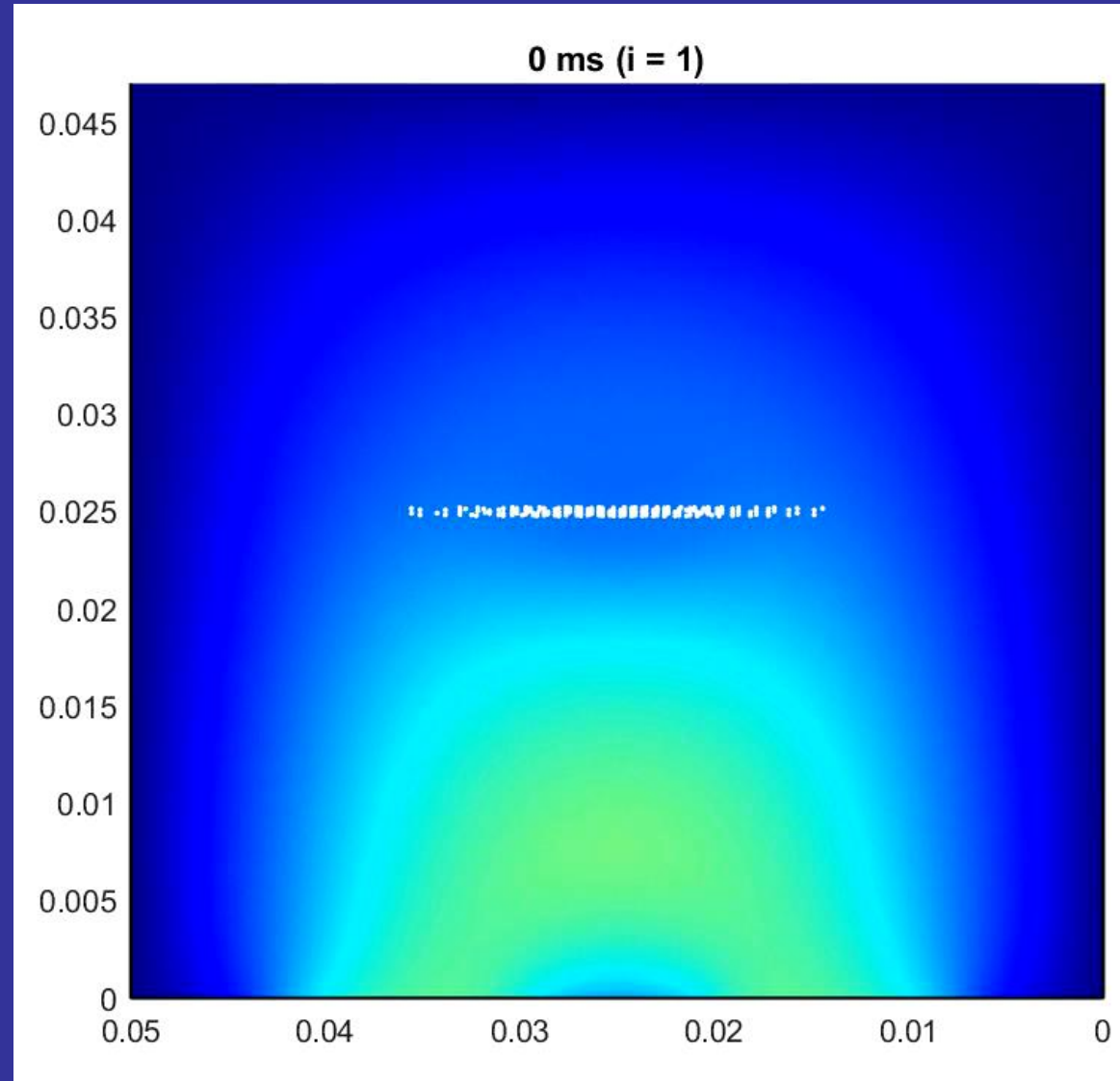
Void fraction

Evolution of „smeared out“ void fraction in time



Cluster formation and dynamics

Big bubble clusters repelled from pressure antinode

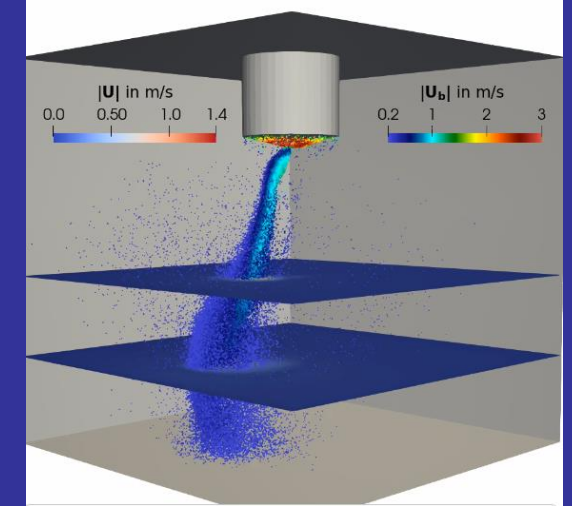


Simulation of a sonotrode system

Localized sound emitter @20kHz in water

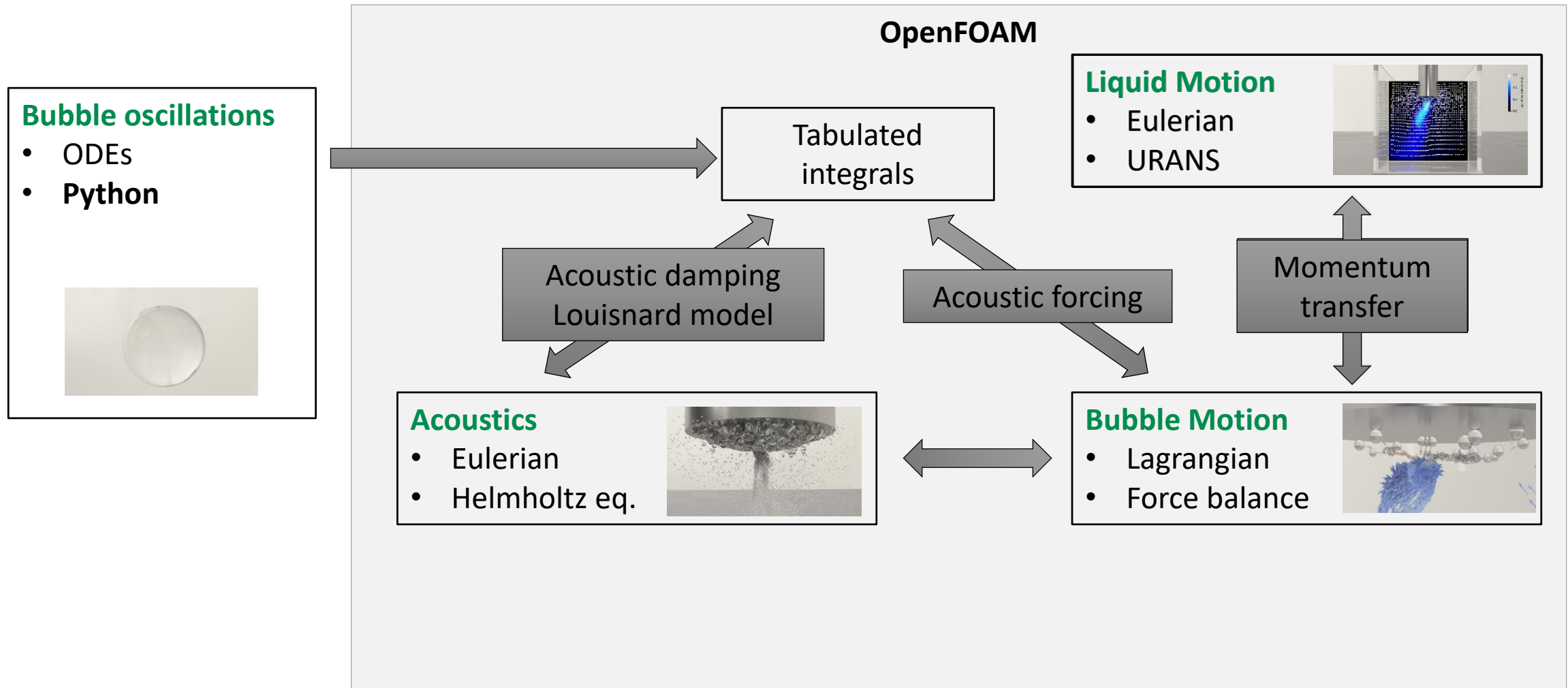
Several coupled phenomena:

- Acoustic field
- Bubble nucleation and motion
- Acoustic field – bubble interaction
- (no bubble-bubble interaction)
- Coupling of lagrangian bubble motion and liquid flow
- Euler-Lagrangian simulation of acoustic cavitation



Sergey Lesnik, 2022
PhD TU Clausthal

Euler-Lagrange Model Overview



Non-linear acoustic wave propagation

- Model from **Louisnard (2012a)**

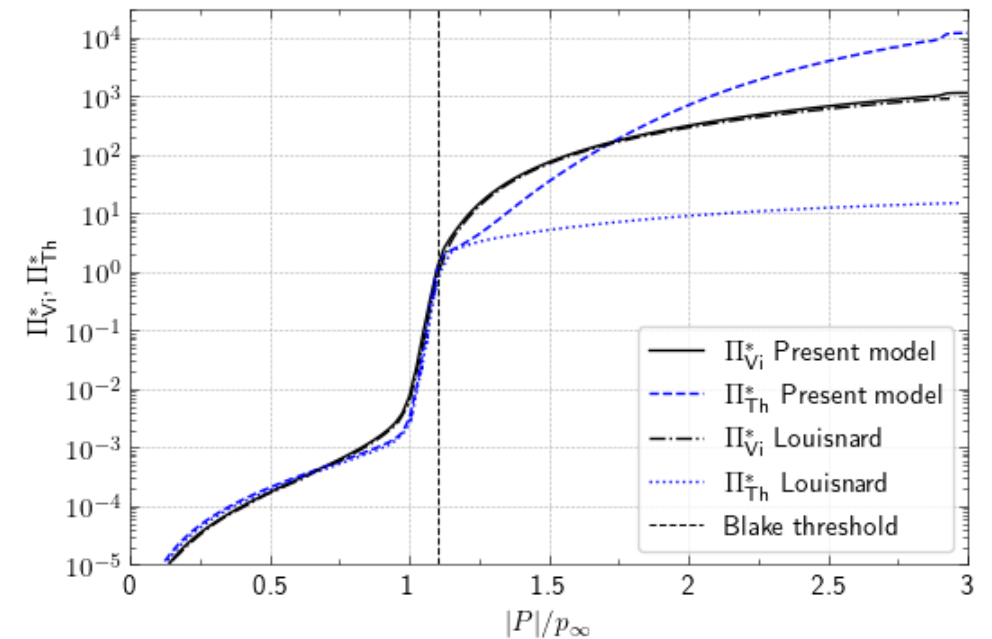
$$\Pi_{Vi} = \frac{1}{T} \int_0^T 16\pi\mu R \dot{R}^2 dt, \quad \Pi_{Th} = \frac{1}{T} \int_0^T p_g \dot{V} dt$$

- Coupling via complex-valued wave number

$$\text{Re}(k_{\text{cav}}^2) = \frac{\omega^2}{c^2} + \frac{3\beta\omega^2}{R_{\text{eq},0}^2(\omega_0^2 - \omega^2)}$$

$$\text{Im}(k_{\text{cav}}^2) = \frac{1}{-2\rho\omega V_C} \sum_i \frac{\Pi_{Vi,i} + \Pi_{Th,i}}{|P_i|^2}$$

$$k^2 = \begin{cases} \text{Re}(k_{\text{cav}}^2) + i \text{Im}(k_{\text{cav}}^2) & \text{if } |P| > P_B \\ \frac{\omega^2}{c^2} & \text{if } |P| \leq P_B \end{cases}$$



Forces Acting on Cavitation Bubble

$$\langle m_b \rangle_T \frac{d\mathbf{u}_b}{dt} = \mathbf{F}_G + \mathbf{F}_{Am} + \mathbf{F}_D + \mathbf{F}_{Bj}$$

- Gravity

$$\mathbf{F}_G = \left(1 - \frac{\rho}{\rho_b}\right) \langle m_b \rangle_T \mathbf{g}$$

- Drag

$$\mathbf{F}_D = 12\pi\mu \langle R \rangle_T (\mathbf{u}_c - \mathbf{u}_b)$$

- Added mass

$$\mathbf{F}_{Am} = \frac{1}{2}\rho \langle V_b \rangle_T \left(\frac{\partial \mathbf{u}_c}{\partial t} + \mathbf{u}_c \cdot \nabla \mathbf{u}_c \right) - \frac{1}{2}\rho \langle V_b \rangle_T \frac{d\mathbf{u}_b}{dt}$$

- Primary Bjerknes (acoustic force)

$$\begin{aligned} \mathbf{F}_{Bj} &= \langle V_b \nabla p \rangle_T \\ &= \text{diag}(\nabla P) (I_C \cos(\phi \mathbf{1} - \boldsymbol{\psi}) + I_S \sin(\phi \mathbf{1} - \boldsymbol{\psi})) \end{aligned}$$

$$I_C = \frac{1}{T} \int_0^T V_b \cos(\omega t) dt, \quad I_S = \frac{1}{T} \int_0^T V_b \sin(\omega t) dt$$

Liquid Motion

- Incompressible Navier-Stokes equations (URANS)
- Interaction with bubbles via source term
- Turbulence model: k- ω -SST

$$\nabla \cdot \mathbf{u} = 0$$

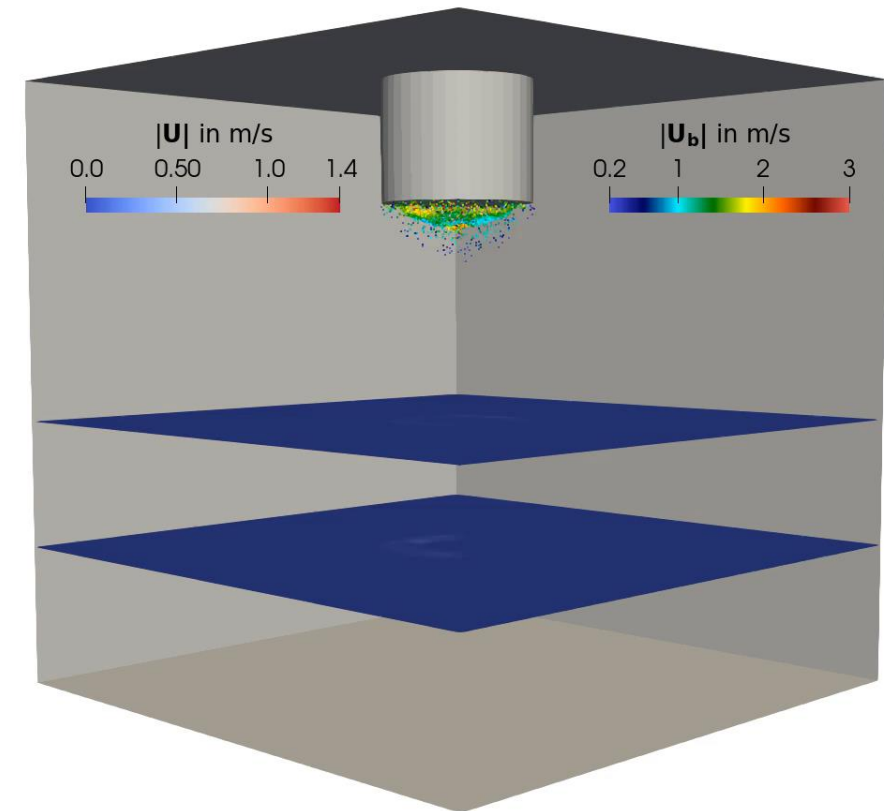
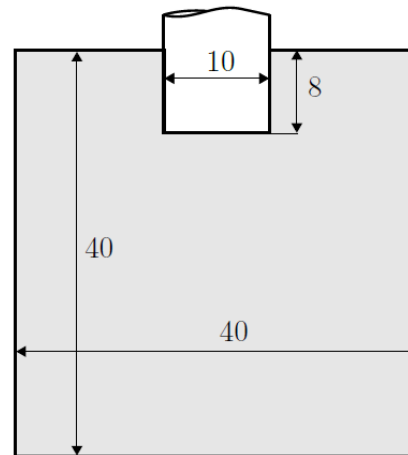
$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} = -\frac{1}{\rho} \nabla p + \nu \nabla^2 \mathbf{u} + \frac{1}{\rho} \mathbf{S}_b$$

$$\mathbf{S}_{b,V_C} = -\frac{1}{V_C} \sum_i \langle m_{\text{eff},i} \rangle_T \frac{\Delta \mathbf{u}_{b,i}}{\Delta t}$$

$$\begin{aligned} \frac{\partial k}{\partial t} + \nabla \cdot (\bar{\mathbf{u}} k) &= \tilde{P}_k - \beta^* \omega + \nabla \cdot \left[\left(\nu + \frac{\nu_t}{\sigma_k} \right) \nabla k \right] & \nu_t &= C \frac{k}{\omega} \\ \frac{\partial \omega}{\partial t} + \nabla \cdot (\bar{\mathbf{u}} \omega) &= \frac{\gamma}{\nu_t} P_k - \beta \omega^2 + \nabla \cdot \left[\left(\nu + \frac{\nu_t}{\sigma_\omega} \right) \nabla \omega \right] + (1 - F_1) 2 \sigma_{\omega 2} \nabla k \cdot \nabla \omega \end{aligned}$$

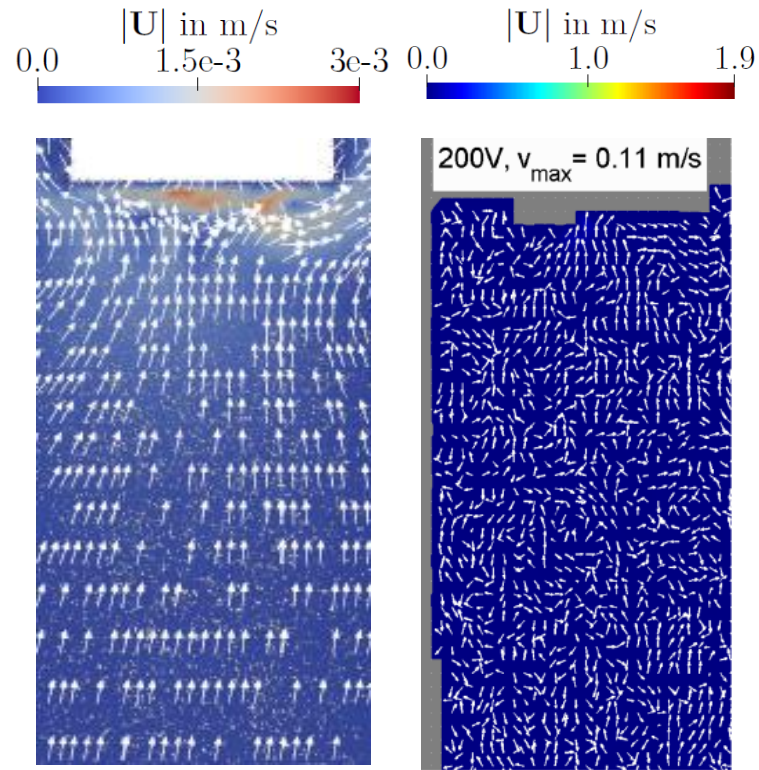
Cubic Tank with 1 cm Sonotrode 20 kHz

- Setup from Nowak, 2013 (tank with a lid)
- 3D calculation
- Video on the right
 - Only bubbles with $|\mathbf{U}_b| > 0.2 \text{ m/s}$ are shown
 - Sonotrode displacement amplitude of $10\mu\text{m}$
 - Void fraction of $3 \cdot 10^{-6}$



Computation vs Experiment

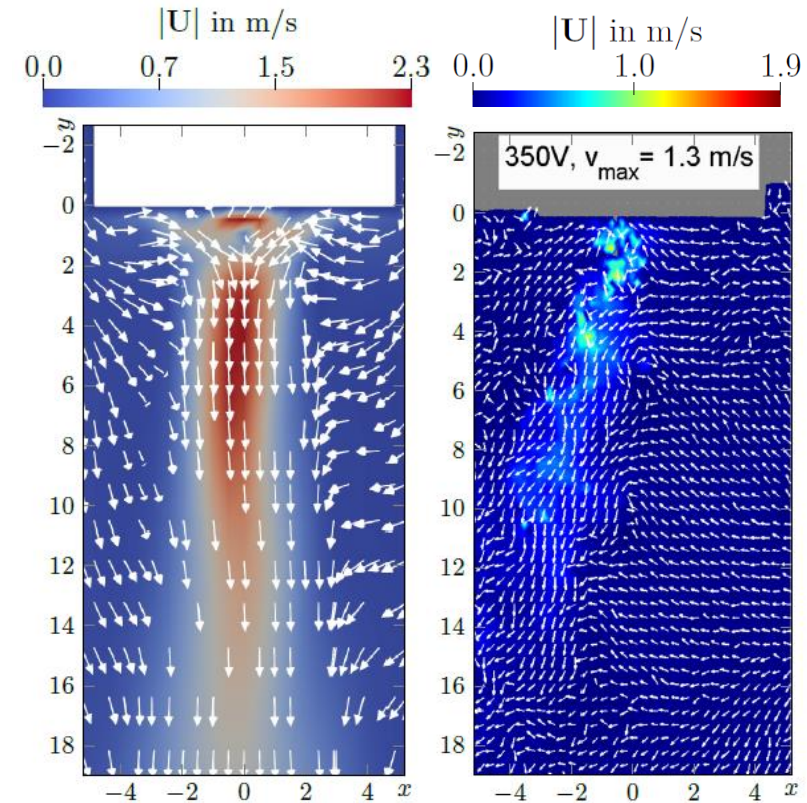
Sonotrode displacement amplitude of $2\ \mu\text{m}$



Computation

Experiment
(Nowak, 2013)

Sonotrode displacement amplitude of $5\ \mu\text{m}$



Computation

Experiment
(Nowak, 2013)

Conclusion and Outlook

- Acoustic cavitation simulations have to deal with **many scales & parameters**
- Generally there is a **high sensitivity** to parameters
- Advanced models **couple** more and more aspects
- A good hierarchical **simplification of scales** is demanded
- Advancing **computer power** will offer more sophisticated schemes

AI...??

- Very **few publications** yet on AI in acoustic cavitation (still big future ;-)
- Promising: **prediction of “yields”** in applications (e.g. chemistry, sound emission...)
- No large **data sets** available (yet)
- **Work to do!**

Thank you for your attention
and enjoy the discussions !!!

